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AN IBM-7090 MONTE CARLO PROGRAM TO
CALCULATE NEUTRON TRANSPORT IN
CYLINDRICALLY SYMMETRIC SHIELDS WITH
PARTICULAR EMPHASIS ON NEUTRON
HEATING IN LIQUID HYDROGEN

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Project Scientist: F. Malmborg

November 1, 1962

Work Performed under UNC Project 2188,
Contract SNPC-5 for the
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ABSTRACT

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An IBM-7090 Monte Carlo program (UNC-90-5) has been written to calculate neutron transport in cylindrically symmetric NERVA configurations with particular emphasis on the heating produced by neutron interactions in liquid hydrogen. A homogenized reactor provides the radiation source, and a shield exists between the fuel tank and the reactor. The assemblage is assumed to be in a vacuum.

Special edits have been prepared to evaluate from the results of the main program:

1. fast neutron dose for near axis points,
2. the spatial distribution of neutron captures in hydrogen,
3. the angle-energy distribution of particles passing through specified planes of the configuration.

A JTHOR

FOREWORD

UNC Memo-5016 which was previously issued on work performed under Contract NAS 5-633 contained a description of and operating instructions for an IBM-7090 computer program. This program calculated the neutron fluxes and gamma ray sources in the reactor, shield, and propellant of a NERVA engine. In addition, neutron heating in the propellant was determined. Since the preparation of that report three special edit routines were prepared which extend considerably the operating utility of the program. In addition, modifications to the operating instructions were made. This report supersedes UNC Memo-5016 and describes the three new special edits and the revised operating instructions.

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1. INTRODUCTION

This report describes a Monte Carlo code developed under contract NAS 5-633, and three special edits developed under contract SNPC-5, for the National Aeronautics and Space Administration. The code is designed to calculate, for a given power distribution in the reactor of a nuclear rocket engine,

1. the neutron energy flux spectrum throughout the reactor, shield, and hydrogen propellant,
2. the heating from neutron interactions throughout the hydrogen propellant,
3. the energy spectrum and spatial and angular distribution of the neutron current leakage out of the reactor, shield, and propellant boundaries,
4. the secondary gamma sources arising from neutron capture and inelastic scattering.

Particular attention was devoted to low energy neutron interactions in hydrogen since such interactions lead to important capture Γ ray sources.

The basic input to the code consists of the geometrical input defining the configuration to be treated, along with the concentrations of the materials present. (See Section 4.) The basic output of the code includes the neutron fluxes and their standard deviations in all reactor and shield regions as well as in certain specified regions in the hydrogen propellant. The heat deposition in prescribed annular regions of the hydrogen propellant is edited. In addition, information concerning leakages and gamma sources is recorded on magnetic tapes for future use (e.g.,

the addition of a gamma tracking code for the determination of heating in hydrogen owing to capture gammas; the extension to tracking neutrons in the air surrounding the rocket).

While no extensive calculations on configurations of interest have been run, it is estimated that problems for typical NERVA configurations will run in under two hours of IBM-7090 time, on a machine having 2 data channels, 10 tape drives, and an on-line printer.

A useful operational feature of the code is that one may force an edit at any time, examine the results, and then, at some other time, continue without loss of any of the results computed prior to the interruption. This allows the user to run until the errors are sufficiently small, with a minimum of difficulty.

2. STATEMENT OF THE PROBLEM

2.1 THE GEOMETRIC HYPOTHESES

Each body of the assemblage, excluding the reactor, is composed of either truncated cones or cylinders joined base to base with the further requirement that the body be convex. The reactor is restricted to be a cylinder in which a power distribution for birth of neutrons is prescribed. The z axis is assumed to be the common axis of symmetry. Each time a neutron emerges from a collision at a point to the right of plane $z = Z_T$ (a constant), the expected heating in each of a number of thin slabs along the extended trajectory of the neutron in the hydrogen propellant is computed. Each slab is divided into a number of annular regions (≤ 4) so that the radial variation of the heating can be determined. The current to the left and to the right across the left edge of each slab is computed. The currents are tabulated according to energy bins.

A typical configuration is given in Fig. 1. The differently shaded regions in Fig. 1 correspond to regions whose material compositions differ. The planes Z_1 , Z_2 , Z_3 , Z_4 , Z_5 , Z_7 , Z_9 , Z_{10} , and Z_{21} are interfaces between regions of differing composition. The planes (Z_4 , Z_9) and (Z_{10} , Z_{14}) along with their radial coordinates (r_2 , r_3) and (r_3 , r_4) specify the truncated cones making up the configuration. In addition, for ($Z_1 \leq z \leq Z_2$, r_1) the cylindrical surface of revolution, along with the planes mentioned above will be referred to as geometric surfaces. All exterior surfaces will be considered geometric surfaces as well. It is possible to desig-

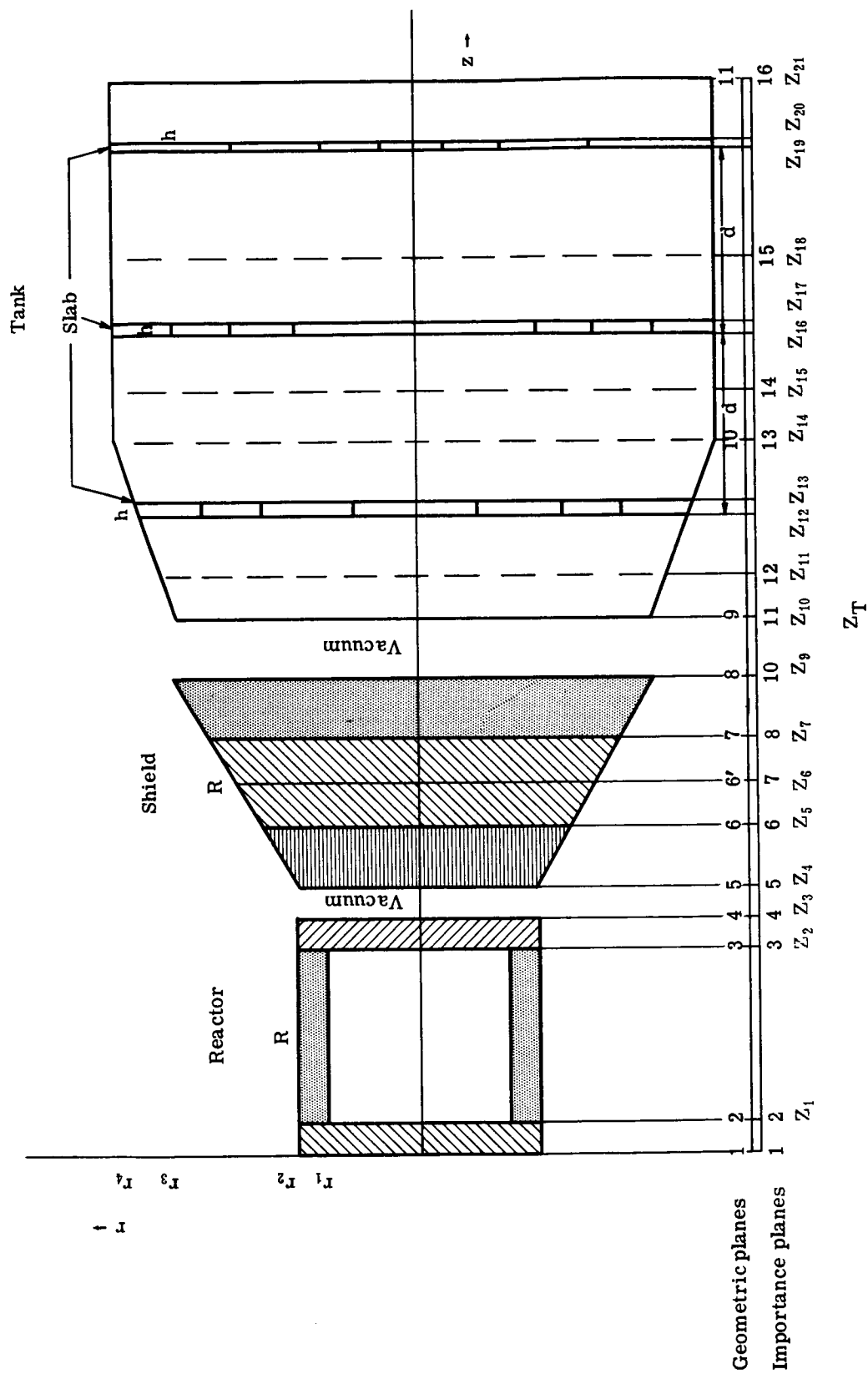


Fig. 1 — Typical configuration

nate any geometric surface of the configuration as a recording surface* (labeled R in Fig. 1, Z_6 , Z_7 , etc.). This means that whenever a particle crosses such a surface its phase space coordinates (x , y , z , ω_x , ω_y , ω_z , E) will be recorded and stored for later use. It is also possible to designate any recording surface as a killing surface and vice versa. If a particle crosses a killing surface, its history is terminated. Importance surfaces are surfaces which divide regions of different statistical weights (Z_6 , Z_{11} , Z_{14} , Z_{18}). Depending on the ratio of the weights, either of two possibilities exists: (1) upon passing through an importance surface latents are created, or (2) Russian roulette is played and with finite probability the history is terminated. The slabs in which the heating is computed are shown with bounding planes (Z_{12} , Z_{13}), (Z_{16} , Z_{17}), (Z_{18} , Z_{20}). The number of distinct annuli (≤ 4) in each slab is assumed to be the same, though their radial positions are arbitrary in each slab.

2.2 THE PHYSICAL HYPOTHESES

The physical hypotheses of the code are now given. The nuclear interactions provided are:

1. Elastic scattering
 - a. Isotropic in the center of mass system
 - b. Anisotropic in the center of mass system
 - c. Isotropic in the laboratory system
 - d. Hydrogen
2. Inelastic scattering
3. Absorptions
4. Low energy ($E \leq 0.08$) hydrogen, following Chistova and Drozdov.¹

*A recording surface may be defined in a body only if all geometric and importance planes in that body are identical.

3. METHOD OF SOLUTION

The overall plan of execution of the code will now be given so that, along with careful study of the appendices and the flow charts, the major highlights of the code may be followed.

A source consisting of the phase space coordinates for the ensemble of neutrons to be processed must be supplied on magnetic tape. The source may either be supplied along the face of the hydrogen propellant (when the reactor and shield are absent), or a power pattern [whose spatial distribution is assumed to be of the form $f(r)g(z)$] throughout the reactor may be given from which the required source tape will be generated. Step functions $f(r)$ and $g(z)$ are given as input. The direction cosines are picked from an isotropic distribution. The energies are chosen from a truncated fission spectrum whose extreme energies E_U , E_L are input.

The executive routine reads 100 source particles at a time into memory. These particles, along with their generated latents, are tracked until they are: (a) absorbed, (b) escaped, (c) degraded below a cutoff energy, or (d) killed by Russian roulette. When these particles and their latents have been processed, the next 100 source particles are read in and the process continues until the desired total of neutron histories has been executed or an edit has been forced.

Let us focus attention on a single neutron's history. Suppose that the neutron's phase space coordinates are given by $(\underline{\omega}, \underline{x}_0, E)$ where $\underline{\omega} = (\omega_x, \omega_y, \omega_z)$ the particle's direction cosines, $\underline{x} = (x, y, z)$ the particle's position coordinates, and E

its energy. We choose a λ from $e^{-\lambda}$ corresponding to the number of mean free paths this neutron will travel before its next interaction. The basic geometric question to be answered (discussed in Appendix 1) is: what is the distance s from \underline{x}_0 to the nearest boundary (geometric surface) of the region containing \underline{x}_0 along the neutron's trajectory? Once s is known, the number of mean free paths $\mu_t s$ is compared against λ . If $\mu_t s < \lambda$, the remaining number of mean free paths is given by $\lambda' = \lambda - \mu_t s$. If $\mu_t s > \lambda$, the particle is regarded as having traveled a distance $s = \lambda / \mu_t$ from \underline{x}_0 along its trajectory. If in both of the above cases the particle passes through an importance plane, splitting or Russian roulette is performed. (See Appendix 2 for more details.) The distance traveled through each collectus* region is recorded in the bin appropriate to the particle's energy, if the body is the reactor or shield.

If the particle crosses a recording or killing surface, its phase space coordinates are recorded and eventually written on magnetic tape. Recording and killing surfaces are restricted to be either geometric planes or surfaces which form part of the boundary. These surfaces are specified by input. If the particle leaves one of the bodies, control is transferred to subroutine AIR to determine the point of intersection, if there is one, with one of the other bodies of the assemblage. If no intersection occurs, an appropriate counter is incremented, and the next history is processed. The distance traveled by the particle in vacuum does not alter the number of mean free paths left. If there is an intersection, then importance sampling is done using the weights appropriate to the exit and entry regions.

At a collision point in either the reactor or shield a neutron event is chosen. First, it is decided with which element the neutron interacts. Next, the type of interaction with that element is chosen. Finally, a new set of direction cosines and an appropriate energy loss are computed (see Reference 2) if the neutron is

*The collectus region corresponding to a point (not on a geometric surface or importance plane) in a body is defined to be the volumetric region bounded by the nearest importance planes and lateral geometric surfaces.

scattered, or appropriate counters are incremented if the neutron is absorbed, degraded, or escapes. (A complete description of all interactions other than low energy hydrogen is outside the scope of this report, but will be found in Reference 2.)

Secondary gammas may be produced as a result of inelastic scattering or absorption. If a gamma producing reaction occurs during the neutron problem, the appropriate information is stored on magnetic tape and may be used in a subsequent gamma ray problem.

Special attention has been given to the low energy neutron interactions with liquid hydrogen in order to obtain a reasonably accurate distribution of neutron captures in the hydrogen tank.

The methods for computing low energy hydrogen neutron interactions in the range $0.02208 \leq E \leq 0.08$ ev where both elastic and inelastic collisions with H_2 molecules are considered, follow the treatment given by Chistova and Drozdov.¹ However, the simplifying approximation that elastic scattering is isotropic in the center of mass system is made. Although the mean value of the cosine of the angle of scattering (in the center of mass system) for an elastic scattering is 0.6 at 0.8 ev, the elastic scattering cross section is small compared to the isotropic inelastic scattering cross section. Consequently, the mean value of the cosine of the angle of scattering, averaged over all scattering processes, is less than 0.2 in absolute value. The values used for σ_{00} and σ_{01} , the elastic and inelastic cross sections per H_2 molecule, are those given in Reference 1. The absorption cross section is determined on the basis of a $1/v$ distribution with $\sigma_a = 0.66b$ at $E = 0.025$ ev.

In the energy range below the first rotational level, we can no longer use the rigid rotator model of Chistova and Drozdov.¹ The only reactions occurring are absorptions and elastic collisions with the hydrogen molecule. For simplicity we assume gas molecules and neglect the binding effects of the liquid. The neutron energy is comparable to the thermal energy of the hydrogen molecule. A

method due to Coveyou, Bate, and Osborne³ is used to include the effect of the thermal motion of the molecules in the collision mechanics. The following assumptions are made.⁴

1. σ_s is constant over the energy range ($0 < E < 0.022$ ev).
2. σ_a has a $1/v$ dependence with $\sigma_a = 0.66b$ at $E = 0.025$ ev.
3. The scattering is isotropic in the center of mass system.
4. The thermal speed distribution of the hydrogen molecules is given by a Maxwell-Boltzmann distribution.

For additional details, see Reference 4.

4. PREPARATION OF INPUT AND OPERATING INSTRUCTIONS

The input preparation along with appropriate operating instructions for the separate sections of the code will now be described. [An element data tape having the cross sections presently in the United Nuclear Corporation library will be supplied, enabling one to manufacture a DATORG tape. While there may be references to sections of other codes (e.g., 9-NIOBE, MISCEL), the instructions given here are self-contained.]

The prescribed limitations listed herein have been arranged according to the compiled dimension statements. These may be altered via a recompilation, if necessary.

The input will be subdivided into three main categories:

1. Input for the DATORG routine of the MISCEL program. This input will be designated as Group-1 data. The output of this routine will be an organized data tape necessary as input for the main program.
2. Input for the Source Tape Generator routine. This input will be designated as Group-2 data. The output of this routine will be a source tape necessary as input for the main program.
3. Input for the main program. The input will be designated as Group-3 data.

4.1 INPUT FOR THE DATORG ROUTINE

4.1.1 Problem Identification Card

Column	Item	Format
1-10	Problem number	Fixed
11-25	Upper energy of cross section data, ev	Floating
26-40	Lower energy of cross section data, ev	Floating
41-45	Number of physical regions, ≤ 30	Fixed
46-72	Blank	

4.1.2 Region Identification Card (one per region)

Column	Item	Format
1-10	Region number	Fixed
11-20	Number of elements in region, ≤ 10	Fixed
21-72	Blank	

4.1.3 Element Card (one per element in the region)

Column	Item	Format
1-5	Integral part of atomic weight	Fixed
6-20	Atomic concentration $\times 10^{-24}$	Floating
21-72	Blank	

Notes:

1. Propellant must be region 1.
2. Each unique material composition is to be given a region number and represented with input cards once only.
3. Regions should be numbered in ascending consecutive order beginning with number 1.
4. Do not use zero concentrations.

4.2 ARRANGEMENT OF OFF-LINE INPUT

I.D. Card
XEQ Card
DATORG Program
Data Card
Group-1 Data
End of File

4.3 COMPUTER CONFIGURATIONS FOR DATORG ROUTINE

Channel	Unit	Tape
A	1	Fortran monitor
	2	Input
	3	BCD output
	5	Element data tape (Input)
B	1	Pool
	2	Pool
	4	Pool
	5	Organized data tape (Output)

Note:

The element data tape is produced by the use of the 9-NIOBE in conjunction with the MISCEL program, and is to be given as input. This tape will be supplied by United Nuclear Corporation.

4.4 OPERATING INSTRUCTIONS

1. Mount and rewind all tapes.
2. Use 32K start card.
3. Normal stop is $(1234)_8$ in SR.
4. Sense switch 2 down – will halt the program at its conclusion with $(1234)_8$ in SR.

4.5 INPUT FOR THE SOURCE TAPE GENERATOR ROUTINE

4.5.1 Energy Card

Column	Item	Format
1-15	Upper source energy, ev	Floating
16-30	Lower source energy, ev	Floating
31-72	Blank	

Notes:

1. The upper energy must be \leq upper energy of cross section data.
2. The lower energy must be \geq lower energy of cross section data.



4.5.2 Reactor Source Distribution Card

Column	Item	Format
1-10	Number of source particles	Floating
11-20	Number of radii plus 1 which define the source regions	Fixed
21-30	Number of planes minus 1 which define the source regions	Fixed
31-72	Blank	

Notes:

1. The number of source particles must be \geq number of particles per statistical group (to be listed on problem parameter card of input).
2. The axis of the configuration is not to be considered as a radius.
(See Fig. 1.)

4.5.3 Source Radius Cards

Column	Item	Format
1-10	Radius of defined source region	Floating
11-20		
21-30		
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

Note:

Each radius defines a cylinder which is continuous between the leftmost and rightmost plane defining the entire source region.

4.5.4 Source Plane Cards

Column	Item	Format
1-10	z-coordinate of plane defining source region	Floating
11-20	↓	↓
21-30		
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

Notes:

1. Leftmost and rightmost bounding planes are to be considered.
2. Each plane is to be listed once only.

4.5.5 Radial Source Probability Cards

Column	Item	Format
1-10	Relative starting probabilities in the radial direction	Floating
11-20	↓	↓
21-30		
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

Note:

List probabilities in order of increasing radius.

4.5.6 Axial Source Probability Cards

Column	Item	Format
1-10	Relative starting probabilities in the axial direction	Floating
11-20	↓	↓
21-30		
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

Notes:

1. List probabilities in order of increasing z-coordinates.
2. The product of the radial and axial probabilities is the probability distribution per unit volume.

4.6 ARRANGEMENT OF OFF-LINE INPUT

I.D. Card
XEQ Card
Source Tape Generator Program
Group-2 Data
End of File

4.7 COMPUTER CONFIGURATION FOR SOURCE TAPE GENERATOR ROUTINE

Channel	Unit	Tape	Logical Designation
A	1	Fortran monitor	1
	2	Input	5
	3	Output (BCD)	6
	4	Pool	4
	6	Source tape (Output)	11
B	1	Pool	8
	2	Pool	2
	3	Pool	3
	4	Pool	7

4.8 OPERATING INSTRUCTIONS

1. Mount and rewind all tapes.
2. Use 32K start card.
3. Sense switch 4 down – produces BCD output on A-3 in addition to the source tape on A-6.

4.9 INPUT FOR THE MAIN PROGRAM

4.9.1 Problem Parameter Card

Column	Item	Format
1-5	Number of bodies involved, 1 or 3	Fixed ↓ Floating
6-10	Total number of geometric planes, ≤ 25	
11-15	Total number of weighting planes, ≤ 30	
16-20	Type of assemblage: 0 = tank only, 1 = entire assemblage	
21-25	Number of energies defining energy bins, ≤ 11	
26-30	Maximum size of latent table, use 30	
31-35	Number of particles per statistical group, use 20	
36-40	Number related to source particles, use 100	
41-45	Record gamma sources on tape: 0=no, 1 = yes	
46-50	Record recording surface particle co- ordinate on tape: 0=no, 1=yes	
51-60	Number of source particles to be proc- essed	Floating
61-72	Blank	

Notes:

1. Every weighting plane in the reactor only must coincide with a geometric plane.
2. The size of a statistical group may be ≤ 100 , but must be such that its product with an integral number equals 100.
3. The desired number of source particles to be processed must be an integral multiple of 100.
4. Every geometric plane is also a weighting plane.
5. If any body of the assemblage has a recording or killing surface, then all weighting planes in that body must be geometric planes.

4.9.2 Bounding Surface Card (one card per body)

Column	Item	Format
1-5	Left geometric plane number	Fixed
6-10	Right geometric plane number	Fixed
11-22	Left z-coordinate	Floating
23-34	Right z-coordinate	Floating
35-46	Radius of bounding cylinder	Floating
47-49	Recording or killing surface index: 0 = none, 1 = either or both	Fixed
50-72	Blank	

Notes:

1. Leftmost plane of first body in assemblage = number 1.
2. Plane numbers are to be in ascending consecutive order.

4.9.3 Annulus Card (as many cards as required)

Column	Item	Format
1-10	Number of annuli to the right of each geometric plane, ≤ 5	Fixed
11-20	↓	↓
21-30		
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

Note:

The numbers to be listed for the rightmost planes of the reactor and shield are to be the same as the immediately preceding planes, whereas no number is to be entered for the rightmost plane of the tank.

4.9.4 Geometric Plane Coordinate Card (as many cards as required)

Column	Item	Format
1-10	z-coordinate of geometric plane	Floating
11-20	↓	↓

Column	Item	Format
21-30	z-coordinate of geometric plane	Floating
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

4.9.5 Weighting Plane Coordinate Card (as many cards as required)

Column	Item	Format
1-10	z-coordinate of weighting plane	Floating
11-20		
21-30		
31-40		
41-50		
51-60		
61-70		
71-72		
	Blank	

4.9.6 Geometric Plane Outer Radius Card (as many cards as required)

Column	Item	Format
1-10	Outermost radius of geometric plane	Floating
11-20		
21-30		
31-40		
41-50		
51-60		
61-70		
71-72		
	Blank	

4.9.7 Geometric Plane Card (one card per geometric plane; as many cards as required)

Column	Item	Format
1-10	Radius of body to the right of the plane	Floating
11-20		
21-30		

Column	Item	Format
31-40	Radius of body to the right of the plane	Floating
41-50	Radius of body to the right of the plane	Floating
51-72	Blank	

Notes:

1. Radii are to be in ascending order.
2. Do not supply a card for the rightmost plane in the entire assemblage (i.e., tank).
3. If a plane is a rightmost plane of the reactor or the shield, the radii to be listed should correspond to those listed for the preceding plane.

4.9.8 Reactor and Shield Neutron History Cutoff Energy Card

Column	Item	Format
1-15	Cutoff energy, ev	Floating
16-72	Blank	

Note:

If reactor and shield are absent, do not supply this card.

4.9.9 Tank Parameter Card

Column	Item	Format
1-10	$1 \leq \text{number of annuli per slab} \leq 4$	Fixed
11-20	$2 \leq \text{number of slabs in tank} \leq 15$	Fixed
21-30	z-coordinate of leftmost plane of tank	Floating
31-40	Slab thickness, cm	Floating
41-50	Distance between corresponding edges of adjacent slabs	Floating
51-72	Blank	

Notes:

1. Each slab must contain the same number of annuli and be of the same thickness, (h).
2. Distance between slabs is to be constant, (d - h).

4.9.10 Tank Hydrogen Information Card

Column	Item	Format
1-15	Cutoff energy for flux, current, heat calculations	Floating
16-30	Cutoff energy for neutron history processing	↓
31-45	Hydrogen concentration = $(\rho N_0/A) \times$ volume fraction	
46-72	Blank	

Note:

Hydrogen concentration must be identical to concentration in fuel tank listed in Group-1 data.

4.9.11 Slab Annuli Card (one card per slab)

Column	Item	Format
1-10	Outer radius of annulus	Floating
11-20	↓	↓
21-30		
31-40		
41-72	Blank	

Note:

The radius of the innermost annulus is to be listed first.

4.9.12 Weight per Region Card (as many cards as required)

Column	Item	Format
1-10	Importance region weight	Floating
11-20	↓	↓
21-30		
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

Notes:

1. The weight of the leftmost region is to be listed first.
2. Regions external to the configuration should have a weight of zero.

4.9.13 Energy Bin Card (as many cards as required)

Column	Item	Format
1-10	Energy defining the energy bins	Floating
11-20	↓	↓
21-30		
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

Notes:

1. First energy is the lowest and must be \leq all neutron history cutoff energies.
2. Maximum number of energies is 11.

4.9.14 Tank Slab Bounding Plane Card (as many cards as required)

Column	Item	Format
1-10	z-coordinate of leftmost plane of tank	Floating
11-20	z-coordinate of slab bounding planes	↓
21-30	↓	
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

Notes:

1. First z-coordinate must define leftmost plane of tank.
2. Left and right coordinates respectively of each slab are to be listed.
3. Last z-coordinate must define rightmost plane of tank.
4. If the coordinate of the left plane of the first slab coincides with the coordinate of the leftmost plane of the tank, list the coordinate once only.
5. All coordinates must be listed in ascending order with no duplication.

4.9.15 Collectus Region Card

Column	Item	Format
1-10	Number of collectus regions	Fixed
11-72	Blank	

When any recording or killing surfaces are present, the following cards are to be used:

4.9.16 Recording Surface Card * (one card per collectus region)

Column	Item		Format
1-10	Left plane index	} 0 = no recording 1 = recording	Fixed
11-20	Outer lateral surface index		Fixed
21-30	Right plane index		Fixed
31-40	Inner lateral surface index		Fixed
41-72	Blank		

4.9.17 Killing Surface Card (one card per killing region)

Column	Item		Format
1-10	Left plane index	} 0 = no killing 1 = killing	Fixed
11-20	Outer surface index		Fixed
21-30	Right plane index		Fixed
31-72	Blank		

4.9.18 Region Composition Index Card (one card per geometric plane)

Column	Item	Format
1-10	Region composition number	Fixed
11-20	↓	↓
21-30		
31-40		
41-72	Blank	

*A recording surface may be defined in a body only if all geometric and importance planes in that body are identical.

Notes:

1. If a region is external to the configuration (i.e., regions in between bodies), list a zero for the composition number.
2. Similar compositions have identical mixtures of elements.

4.9.19 Direction Card

Column	Item	Format
1-10	N (see note)	Fixed
11-20	Direction printout: 0 = no, 1 = yes	Fixed
21-72	Blank	

Note:

2^N isotropically distributed directions in space to be used in low temperature hydrogen reactions. (Use N = 10.)

4.9.20 Hydrogen Reaction-3 Card

Column	Item	Format
1-10	Number of velocities plus 1 (see note)	Fixed
11-72	Blank	

Note:

Velocities at which the total macroscopic cross section will be computed for use in interactions. Maximum number of velocities that can be entered = 11.

4.9.21 Velocity Card (as many cards as required)

Column	Item	Format
1-14	Velocities, cm/sec	Floating
15-28	↓	↓
29-42		
43-56		
57-70	↓	↓
71-72	Blank	

Note:

See Appendix 4 for list of recommended velocity values.

4.10 ARRANGEMENT OF OFF-LINE INPUT

I.D. Card
XEQ Card
Binary Program Deck
Group-3 Data
End of File

Note:

The program deck includes a data card.

4.11 COMPUTER CONFIGURATION

Channel	Unit	Tape	Logical Designation
A	1	Fortran monitor	1
	2	Input	5
	3	Output	6
	4	Pool or recording surface data (Output)	4
	6	Source tape (Input)	11
B	1	Pool or forced edit core dump tape	8
	2	Pool or gamma source data (Output)	2
	3	Pool	3
	4	Pool	7
	5	Organized data tape (Input)	10

4.12 OPERATING INSTRUCTIONS

1. Mount and rewind all tapes.
2. Use 32K start card.
3. Sense switch options

Switch 1 down – traces hydrogen reactions in the tank.

Switch 2 down – gives on-line printout.

Switch 4 down – lets program pause before beginning.

Switch 5 down – dumps the core storage on B-1 after it is rewound and

and edits the results on A-3. The number of particles considered is modulo the number of particles per statistical group. (See problem parameter card.)

Note:

Remove and save A-2, 4, 6, and B-1, 2.

4.13 RESTART PROCEDURE

4.13.1 Computer Configuration

Channel	Unit	Tape
A	1	Core storage dump tape (Input)
	3	Output (New tape)
	4	Recording surface data (Input)
	6	Source tape (Input)
B	2	Gamma source data (Input)

4.13.2 Operating Instructions

1. Mount and rewind all tapes.
2. Press clear, load tape. HPR6 will appear, then press START.
3. Normal stop is 17171 in instruction counter if actual number of particles processed equals the desired number of particles to be processed (Input No.). Otherwise, the forced edit procedure must be employed and the program will stop with an HPR6. At this point remove tapes A-1, 3, 4, 6, and B-2.

5. DESCRIPTION OF THE OUTPUT

Items included in the edited output are listed below.

1. Desired number of source particles processed, number of particles actually processed.
2. Number of particles in a group, latent table size, number of energy bins, index to denote whether the tank only was involved.
3. Number of bodies involved in the problem, number of geometric planes, number of weighting planes.
4. Body number, leftmost plane index, rightmost plane index, leftmost z-coordinate, rightmost z-coordinate.
5. Radius of bounding cylinder, recording and killing surface index.

Note:

Items 4 and 5 are repeated for each body number.

6. Geometric plane number, number of annuli, z-coordinate, outer radius.
7. Collectus region number, deaths, births, degradations, absorptions.
8. Recording surface matrix, killing surface matrix.
9. Number of particles (N) entering body between geometric planes "K" and "K + 1."

10. Number of slabs in tank, slab thickness, center-to-center distance between slabs in tank, number of annuli per slab.
11. Statistical estimation cutoff energy, hydrogen cutoff energy, ev.
12. Coordinates of slab edges and tank ends.
13. Radius of annulus "Q" of slab "L."
14. Annulus volume, volumetric heating [(energy, ev/unit vol-energy bin)/source particle] standard deviation of heating.

Notes:

- a. The leftmost column is the slab number.
- b. The values listed in item 14 are printed beneath each other for each annulus.
15. For each slab, the following data: slab number, bin energies, positive current, standard deviation of positive current, negative current, standard deviation of negative current.
16. For each slab, the following data: slab number, annuli numbers, bin energies, flux per unit energy per source particle, standard deviation of the flux.
17. For each body, the following data: body number, number of particles that escaped from the body.
18. Particle balance of entire assemblage.
19. Outer radii of annuli between geometric planes.

Note:

The leftmost column is the plane number.

20. Reactor-shield cutoff energy, ev.
21. For each region, the following data: region number, region volume, bin energies, flux per unit energy per source particle, standard deviation of the flux.

5.1 ON-LINE PRINTOUT (SENSE SWITCH 2 OPTION)

1. Number of source particles actually processed up to time sense switch 2 is depressed, and number of source particles on which edit would be performed if a forced edit occurred at the time the on-line printing appeared.
2. Collectus region number, number of births, deaths, degradations, absorptions, and gamma sources occurring in the collectus region. This material is printed for all collectus regions.
3. Number of particles escaped from assemblage from each body of the assemblage is printed across the page.
4. If neutrons are being traced through a three-body assemblage, then the number of particles entering the bodies between all geometric planes is printed across the page.

6. A DESCRIPTION OF THREE SUBPROGRAMS WHICH PERFORM SPECIAL EDIT FUNCTIONS ON OUTPUT TAPES OF CODE UNC-90-5

6.1 SUMMARY

This report contains a description of the three subroutines listed below, together with appropriate input and operation instructions:

1. Dose Calculations
2. Propellant Captures
3. Transmitted Particle Sorting

6.1.1 Dose Calculations – DOSE

For a given input dose response function, the dose on a specified plane is computed from data generated by code UNC-90-5 and stored on the Recording Surface Tape.

6.1.2 Propellant Captures – CAPTS

Neutron absorptions occurring in the propellant are sorted into propellant annular bins. The annular bin structure is required input for the program. The Gamma Source Tape, generated by code UNC-90-5, is required by CAPTS because it contains the absorption data.

6.1.3 Transmitted Particle Sorting – BEDIT

Particles passing through a recording plane specified in UNC-90-5 have their phase coordinates recorded on the Recording Surface Tape. This tape is processed by the BEDIT program so that the particles are sorted into desired energy, angular, and radial bins.

6.2 DOSE CALCULATIONS

6.2.1 Program DOSE

The dose per unit area in specified annular regions of a target plane to the right of a recording plane of interest is calculated as follows:

A particle (which may be a latent), emerging from a recording plane, is traced to the target plane assuming vacuum exists between the recording and target planes. If the radius of the particle at the target plane is greater than the maximum radius of the target, the particle is ignored. Otherwise, linear interpolation on energy at the particle energy E_p is employed on the input dose response function, $D(E)$, to determine $D(E_p)$. Since the flux, in an annular region with radii r_i, r_{i+1} , ($r_i < r_{i+1}$), in the target plane with finite thickness reduces to $1/\omega_z \pi (r_{i+1}^2 - r_i^2)$ in the limit as the plane's thickness approaches zero, the contribution to the dose per unit area TD_{i+1} in the annular region (r_i, r_{i+1}) is $D(E_p)/\pi \omega_z (r_{i+1}^2 - r_i^2)$ where ω_z is the cosine of the angle the particle's trajectory makes with the z (axial) axis.

The dose per unit area, TD_{i+1} , in annular region (r_i, r_{i+1}) , is the sum of the contributions of the form (1) of all the particles passing through the recording plane and striking the annulus, multiplied by the reciprocal W of the importance function at the recording plane, i.e., $TD_{i+1} = W \sum D(E_p)/\pi \omega_z (r_{i+1}^2 - r_i^2)$.*

6.2.2 Input for DOSE

Information contained on cards used for DOSE input and its column location is described below.

Parameter Card

Column	Item	Format
1-10	No. of records of recording surface data tape to be processed	Floating
11-20	Recording plane axial (z) coordinate	↓
21-30	Target plane axial (z) coordinate	

*The summation is taken over all particles passing through the recording plane and striking annulus r_{i+1}, r_i .

Column	Item	Format
31-40	No. of radii into which the target plane is divided	Floating
41-72	Blank	

Notes:

1. The axis is not to be considered as a radius.
2. Only one recording and one target plane is permitted.
3. The plane on which the dose is to be calculated is called the target plane.

Radius Card

Column	Item	Format
1-10	Outer radius of annulus	Floating
11-20	↓	↓
21-30		
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

Notes:

1. Innermost annulus is to be listed first.
2. The first annulus must correspond to a disk.
3. The maximum number of radii permitted is 11.
4. Use as many cards as needed.

Weight Card

Column	Item	Format
1-10	Reciprocal of importance function at recording plane	Floating
11-72	Blank	

Energy Number Card

Column	Item	Format
1-10	No. of energy values at which dose response function input is defined	Fixed
11-72	Blank	

Energy Card

Column	Item	Format
1-14	Energy at which dose response function input is defined	Floating
15-28	↓	↓
29-42		
43-56		
57-70		
71-72	Blank	

Notes:

1. Energy must be in units of ev.
2. Lowest energy is to be listed first.
3. A maximum of 100 energy values is permitted.
4. Use as many cards as required.

Dose Response Function Input Card

Column	Item	Format
1-14	Dose response function	Floating
15-28	↓	↓
29-42		
43-56		
57-70		
71-72	Blank	

Notes:

1. The dose response function corresponding to the lowest energy value is to be listed first.
2. A maximum of 100 energy values is permitted.
3. Use as many cards as required.

6.2.3 Arrangement of Off-Line Input

I.D. Card
XEQ Card
Binary Program Deck
Input Data
End of File

Computer Configuration

Channel	Unit	Tape	Logical Designation
A	1	Fortran monitor	1
	2	Input	5
	3	Output	6
B	7	Recording surface data tape (Input)	14

6.2.4 Operating Instructions

1. Mount and rewind all tapes.
2. Use 32K start card.
3. Sense switches – none.

Note:

Save B-7 since its data are unaltered by the DOSE program.

6.2.5 Output of DOSE

A brief description of the edited output of the off-line printer is given below.

Page 1

The input data are printed out in the same form as they appear on INPUT DATA cards. However, these are unlabeled. In some cases the field width may be wider than the field of the input.

Page 2

The input data are printed out with labels.

Page 3

Annulus number and dose between the defining radii of the annulus are printed.

6.3 PROPELLANT CAPTURES

6.3.1 Program CAPTS

This program sorts the number of absorptions in the propellant into defined volumetric regions of propellant. The original data are contained on the Gamma-Source Data tape. Bin regions are restricted* to annular regions along the z-axis.

6.3.2 Input for CAPTS

Information contained on cards used for CAPTS input and its column location is described below:

Parameter Card

Column	Item	Format
1-10	No. of records of gamma-source data tape to be processed	Floating
11-72	Blank	

Axial Division Card

Column	Item	Format
1-10	No. of spaces plus one into which the z-axis is divided	Fixed

Note:

The maximum number of planes permitted is 11.

z-Plane Card

Column	Item	Format
1-10	Axial coordinate of annuli bounding plane	Floating
11-20	↓	↓
21-30		
31-40		

*The nth radius (where it exists) of each axial region must be the same for all axial regions, e.g., the radii of the innermost annulus of every axial region must be identical.

Column	Item	Format
41-50	Axial coordinate of annuli bounding plane	Floating
51-60	↓	↓
61-70		
71-72		
	Blank	

Notes:

1. Lowest z-value is to be listed first.
2. No z-coordinate is to be listed more than once.
3. The unit of z is cm.
4. Use as many cards as required.

Annuli Index Card

Column	Item	Format
1-10	No. of annuli to the right of z-plane	Fixed
11-72	Blank	

Notes:

1. This type of card must appear for all z-planes except the rightmost one of the set of input planes previously defined.
2. The maximum number of annuli associated with each plane is 25.
3. Each of these cards must be immediately followed by its corresponding radii card defined below.

Radii Card

Column	Item	Format
1-10	Radii of region to the right of the plane	Floating
11-20	↓	↓
21-30		
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

Notes:

1. Radii are to be in ascending order.
2. Use as many cards as required.

6.3.3 Arrangement of Off-Line Input

Same as for DOSE.

Computer Configuration

Channel	Unit		Logical Designation
A	1	Fortran monitor	1
	2	Input	5
	3	Output	6
B	8	Gamma source data tape (Input)	16

6.3.4 Operating Instructions

1. Mount and rewind all tapes.
2. Use 32K start card.
3. Sense switches – none.

Note:

Save B-8 since its data are unaltered by the CAPTS program.

6.3.5 Output of CAPTS

A brief description of the edited output on the off-line printer is given below.

Page 1

The input data are printed out in the same form as they appear on the INPUT DATA cards. However, these are unlabeled. In some cases the field width may be wider than the field of the input.

Page 2

The number of particles (including latents) that are absorbed in the annular regions between the specified z planes is listed.

6.4 TRANSMITTED PARTICLE SORTING

6.4.1 Program BEDIT

Given a z-plane that was specified as a recording plane in the main program, this program processes the data on the Recording Surface tape, and sorts the particles (including latents) heading in the positive z-direction into specified energy and angular bins for each defined annular region of the recording plane. Depending on whether or not the particles' extended trajectories intersect a plane (with specified z-coordinate and outer radius) to the right of the recording plane, the particles are further divided into groups of hits and misses as shown in Fig. 2.

The radius, r , of a particle at the target plane is given as follows:

Let z' be the axial coordinate of the target plane. Let z be the axial coordinate of the recording plane. Let x, y be the particle's x and y coordinate values at the recording plane. Let $\omega_x, \omega_y, \omega_z$ be the particle's direction cosines. Then,


$$r = \sqrt{\left[x + \omega_x \left(\frac{z' - z}{\omega_z} \right) \right]^2 + \left[y + \omega_y \left(\frac{z' - z}{\omega_z} \right) \right]^2}$$

If $r > R'$ (where R' is the target radius), the particle is said to have missed the target; otherwise it hits.

6.4.2 Input for BEDIT

Information contained on cards used for BEDIT input and its column locations is described below.

Parameter Card

Column	Item	Format
1-10	No. of records on recording surface data tape to be processed	Floating
11-20	No. concerned with edit type (use 3)	
21-30	No. concerned with recording planes (use 3)	
31-72	Blank	

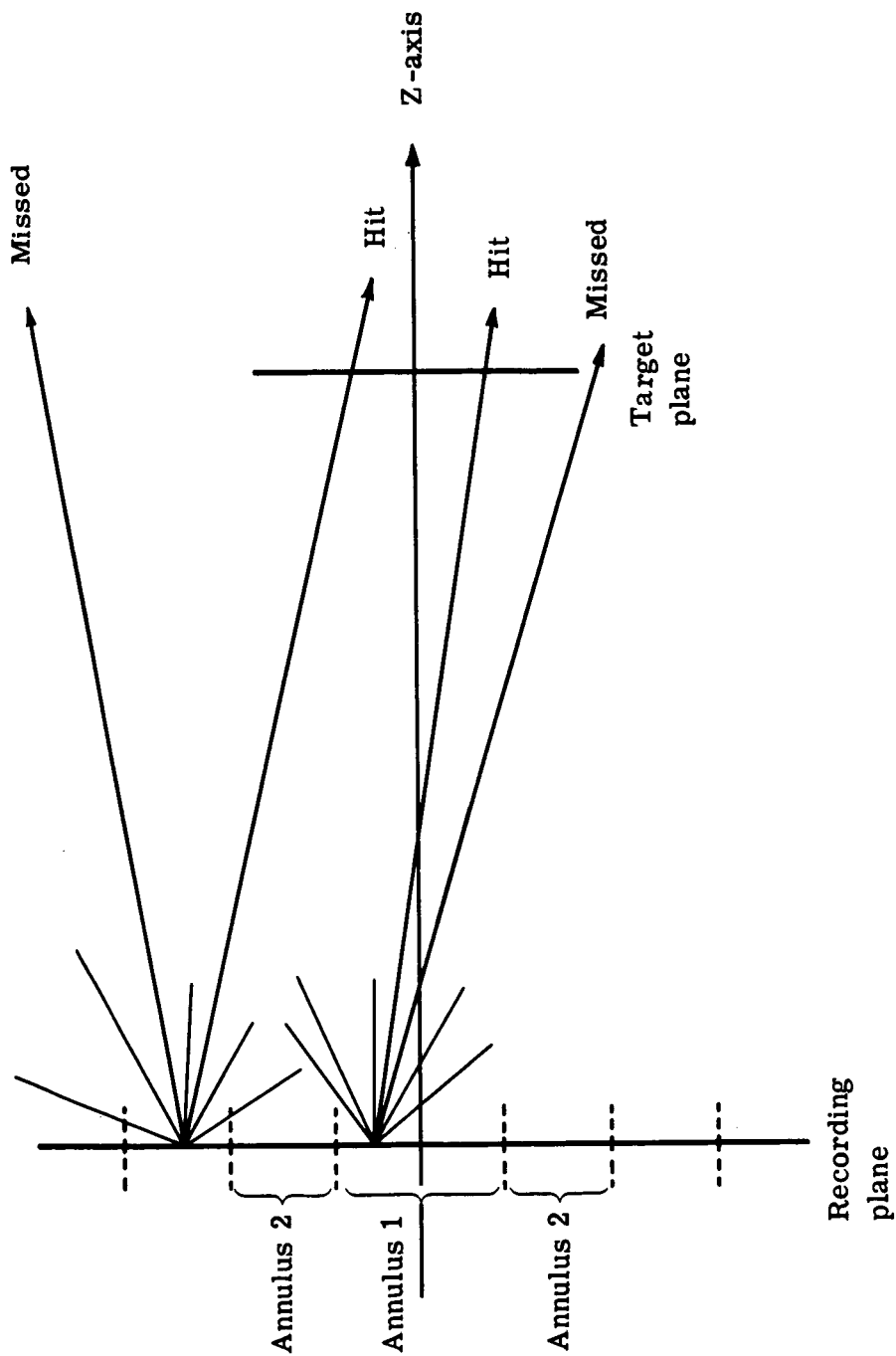


Fig. 2 — Particle divisions

Geometry Card

Column	Item	Format
1-10	Axial (z) recording plane coordinate	Floating
11-20	Axial target plane coordinate	↓
21-30	No. related to annuli definition (use -1)	
31-40	No. related to angle definitions (use 0)	
41-50	No. related to energy definitions (use 0)	
51-60	Target plane outer radius	
61-72	Blank	

Radial Index Card

Column	Item	Format
1-10	No. of radii into which the recording plane is divided (≤ 10)	Floating
11-72	Blank	

Note:

The z-axis is not to be considered a radius.

Radius Card

Column	Item	Format
1-10	Outer radius of annuli of recording plane	Floating
11-20	↓	↓
21-30		
31-40		
41-50		
51-60		
61-70	↓	↓
71-72		
	Blank	

Notes:

1. The radii are to be listed in ascending order.
2. No radius value is to be repeated.
3. Use as many cards as required.

Angle Index Card

Column	Item	Format
1-10	No. of angular bins associated with each annulus (≤ 10)	Floating
11-72	Blank	

Notes:

1. Every annulus has the same number of (and identical) angular bins.
2. The angle range is from 0° to 90° .
3. The end point of the lowest angular bin must include 0° .

Angle Card

Column	Item	Format
1-10	Angles defining angular bins (≤ 10)	Floating
11-20		
21-30		
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

Notes:

1. Angles are to be in degrees.
2. Angles are to be in ascending order.
3. 0° (the lower endpoint of the lowest angular bin) is not to be included on the card.
4. These angles define the angular bins for all annular regions of the recording plane.
5. Use as many cards as required.

Energy Index Card

Column	Item	Format
1-10	No. of energies defining energy bins (≤ 11)	Floating
11-72	Blank	

Energy Card

Column	Item	Format
1-10	Energies defining energy bins	Floating
11-20		
21-30		
31-40		
41-50		
51-60		
61-70		
71-72	Blank	

Notes:

1. Energies are to be listed in ascending order.
2. Units are ev.
3. These energies define energy bins for all annuli of the recording plane.
4. Use as many cards as required.

6.4.3 Arrangement of Off-Line Input

Same as for DOSE.

Computer Configuration

Same as for CAPTS.

6.4.4 Operating Instructions

Same as for CAPTS.

6.4.5 Output of BEDIT

A brief description of the edited output on the off-line printer is given below.

Page 1

The input data are printed out in the same form as they appear on the INPUT DATA cards. However, these are unlabeled. In some cases the field width may be wider than the field of the input.

Page 2

Recording plane axial coordinate is printed and labeled. Target plane axial coordinate is printed and labeled. Target radius value is printed and labeled.

Page 3 and Succeeding Pages

Two methods in which the number of particles in the various bins are printed are listed below.

1. First Method

On each page a matrix of numbers for one annular region (starting with the innermost) is printed. The matrix consists of the number of particles in the bins defined by the angles listed across the page and the energies listed down the page.

2. Second Method

On each page a matrix of numbers for one energy interval (starting with the lowest) is printed. The matrix consists of the number of particles in the bins defined by the angles listed across the page and the radii listed down the page.

7. APPENDICES

7.1 APPENDIX 1 – GEOMETRIC TRACKING

Given the neutron's phase space coordinates (i.e., an initial position \underline{x}_0 , direction $\underline{\omega}$ and energy E), a number of mean free paths is selected, (λ from $e^{-\lambda}$). The basic problem related to the geometric configuration may be stated as follows. What is the distance s from \underline{x}_0 to the boundary of the region containing \underline{x}_0 along the neutron's trajectory? In analyzing the problem it is useful to introduce Cartesian coordinates. Let (x,y,z) be a point a distance of s along the trajectory having direction cosines $(\omega_x, \omega_y, \omega_z)$, then

$$\begin{aligned}x &= x_0 + \omega_x s \\y &= y_0 + \omega_y s \\z &= z_0 + \omega_z s\end{aligned}\tag{1}$$

It is convenient to introduce the radial distance r from the point (x,y,z) to the z -axis. Accordingly,

$$r^2 = x^2 + y^2; \quad r_0^2 = x_0^2 + y_0^2.\tag{2}$$

In addition, if $B = x_0\omega_x + y_0\omega_y$, $A = \omega_x^2 + \omega_y^2$, then

$$r^2 = r_0^2 + 2Bs + As^2.\tag{3}$$

All surfaces of revolution comprising the lateral surfaces of the reactor, shield, and hydrogen tank may be considered to be of the form

$$r = \alpha_{k0} + \alpha_{k1}z.\tag{4}$$

To find the intersection of the neutron's trajectory with such surfaces of revolution, one must solve for the positive root of

$$(\alpha_{k0} + \alpha_{k1}z)^2 = r_0^2 + 2Bs + As^2. \quad (5)$$

Setting $r_s = \alpha_{k0} + \alpha_{k1}z$; $A_0 = A - \alpha_{k1}^2 \omega_z^2$; $B_0 = B - r_s \alpha_{k1} \omega_z$; $C_0 = r_0^2 - r_s^2$, we get

$$A_0 s^2 + 2B_0 s + C_0 = 0. \quad (6)$$

If the particle is initially inside the region (i.e., $r_0^2 < r_s^2$), the positive root of the equation is given by

$$s_m = \frac{-B_0 + \sqrt{B_0^2 - A_0 C_0}}{A_0}. \quad (7)$$

It is useful to write Eq. 3 in another form. Consider a neutron's trajectory in relation to the z-axis. If the two are not parallel, there is a point on the extended trajectory which is closest to the z-axis. Let the coordinates of this point P_c be (r_c, z_c) , and let the arc length s along the ray be measured with P_c as origin and the direction of increasing s given by the direction of motion. Using this new coordinate system, Eq. 3 becomes

$$r^2 = r_c^2 + As^2, \quad (8)$$

or

$$\frac{dr}{ds} = \frac{As}{r}. \quad (9)$$

It is easily seen that dr/ds and s agree in sign. Using this simplifies many of the geometric tracking routines.

7.2 APPENDIX 2 – IMPORTANCE SAMPLING AND STATISTICAL ESTIMATION

We use an importance function which is piecewise constant as a function of z . Importance region k_W is defined by $z_{k_W} \leq z_{k_W+1}$; $k_W = 1, 2, \dots$, and in this region the reciprocal of the importance function assumes the constant value

$W(k_W)$. The planes $z = z_{k_W}$ are the importance planes. The assignment of importance planes is subject to the following two restrictions:

1. Each geometric plane must also be an importance plane.
2. In the reactor each importance plane must also be a geometric plane.

It should be noted that except for the reactor each importance plane need not be a geometric plane.

An example will indicate the manner in which the importance sampling is done. Assume that a particle starting at P intersects the boundary of the region at P' and the segment PP' intersects one or more importance planes. Assume also that in crossing the first importance plane the particle goes from a region of weight W to a region of weight W'. If $W' > W$, then a game of chance is played in which the particle survives with probability W/W' . If $W' < W$ and $W' \neq 0$, let $N_1 = (W/W' - 1)$, [where (x) indicates the integral part of x]. Define $N_2 = W/W' - 1 - N_1$. The N_1 latents are born at the intersection of the flight path with the importance plane, and a game of chance is played with probability N_2 of success, to determine whether an additional latent is born. If it is desired that particles be killed when going from one region to another, their common surface must be designated a killing surface as defined in Section 3. The program interprets $W = 0$ for a region as meaning that region is vacuous and separates adjacent bodies of the assemblage. As long as the particle survives, this process is repeated at each of the importance planes the flight path intersects. If in the above description P' had been the next collision point, the same remarks would apply.

For the purpose of computing heating in the hydrogen propellant, statistical estimation is used. Define a set of thin slabs of thickness h spaced uniformly a distance d apart along the z-axis. Each slab is divided into $q_{\max} \leq 4$ annular regions. The outer radius of the q^{th} annulus of the ℓ^{th} slab is $r_{q,\ell}$. The first slab on the left corresponds to $\ell = 1$ and the innermost annulus to $q = 1$. Whenever a particle emerges from a collision to the right of the plane $z = Z_T$, the following quantities are computed for each of the regions the line of flight intersects:

(1) the expected heating $H(q, \ell)$, (2) the tracklength $T(q, \ell, m)$, (3) the current crossing to the right across the left edge of a slab, $C_+(\ell, m)$, (4) the current crossing to the left across the left edge of a slab, $C_-(\ell, m)$. The index m refers to the energy interval in which the energy of the particle falls. The above quantities are computed in the following manner. Assume that a neutron emerges from a collision at a point P and its line of flight intersects a volume V in the points P' , P'' . The medium is assumed to be homogeneous and of total cross section μ_t . Let the length of PP' be s_0 and the length of $P'P''$ be s_1 . The expected tracklength in the region is given by

$$T = \frac{1}{\mu_t} e^{-\mu_t s_0} (1 - e^{-\mu_t s_1}).$$

In a collision with hydrogen the neutron loses on the average half of its energy so that the expected heating is given by $H = (E/2) T \mu_t$. The expected current across the left edge is equal to the probability that the neutron gets to P' without colliding, i.e., $C = e^{-\mu_t s_0}$.

7.3 APPENDIX 3 - STATISTICS

For the reactor and shield the flux and its standard deviation are computed as follows. Source particles are grouped into G groups of r particles each. The flux per source particle per unit energy in energy interval m is given by

$$F(i, m) = \frac{W(i)}{(E_{m+1} - E_m) V_i(Gr)} \sum_{g=1}^G S_g(i, m) \quad (10)$$

where $S_g(i, m)$ is the sum of the tracklengths of the g^{th} group of source neutrons together with all its corresponding latent particles in region i with energy E satisfying

$$E_m \leq E < E_{m+1}. \quad (11)$$

V_i is the volume of region i and $W(i)$ is the corresponding reciprocal importance function. The standard deviation of the above flux $F(i,m)$ is given by

$$\sigma[F(i,m)] = \frac{F(i,m) G}{\sum_{g=1}^G S_g(i,m)} \sqrt{\frac{1}{G-1} \frac{\sum_{g=1}^G S_g^2(i,m)}{G} - \left[\frac{\sum_{g=1}^G S_g(i,m)}{G} \right]^2} \quad (12)$$

For each slab, ℓ , in the propellant the positive and negative currents through the left edge per source particle per unit energy interval m are given by

$$\begin{aligned} \bar{C}_+(\ell,m) &= \frac{1}{(E_{m+1} - E_m) Gr} \sum_{g=1}^G [C_+(\ell,m)]_g \\ \bar{C}_-(\ell,m) &= \frac{1}{(E_{m+1} - E_m) Gr} \sum_{g=1}^G [C_-(\ell,m)]_g \end{aligned} \quad (13)$$

respectively. $[C_+(\ell,m)]_g$ and $[C_-(\ell,m)]_g$ are the corresponding sums of neutron currents of the g^{th} groups of source neutrons and latents in the energy interval (11).

With proper modifications the heat deposition per unit volume per source particle for each annular slab region and the corresponding flux per unit energy are given as above.

The corresponding standard deviation of the above is (again with proper modifications) treated as in (12).

The reciprocal W of the importance function does not appear explicitly in the above expression for the propellant since it is accounted for each time

the appropriate quantities are computed by the statistical estimation calculation procedure. That is, T, H, and C of Appendix 2, each time they are computed at a collision point, are multiplied by the value of W at that point.

7.4 APPENDIX 4 – RECOMMENDED VELOCITY VALUES

The total macroscopic cross section for the low temperature hydrogen reaction ($0.02208 > E > 0.0$) is calculated by the code and stored in memory in tabular form. For an appropriate particle velocity, table lookup with linear interpolation is performed to evaluate the total macroscopic cross section.

Recommended input velocity values for use in defining the cross section table are listed below. The largest number is listed first.

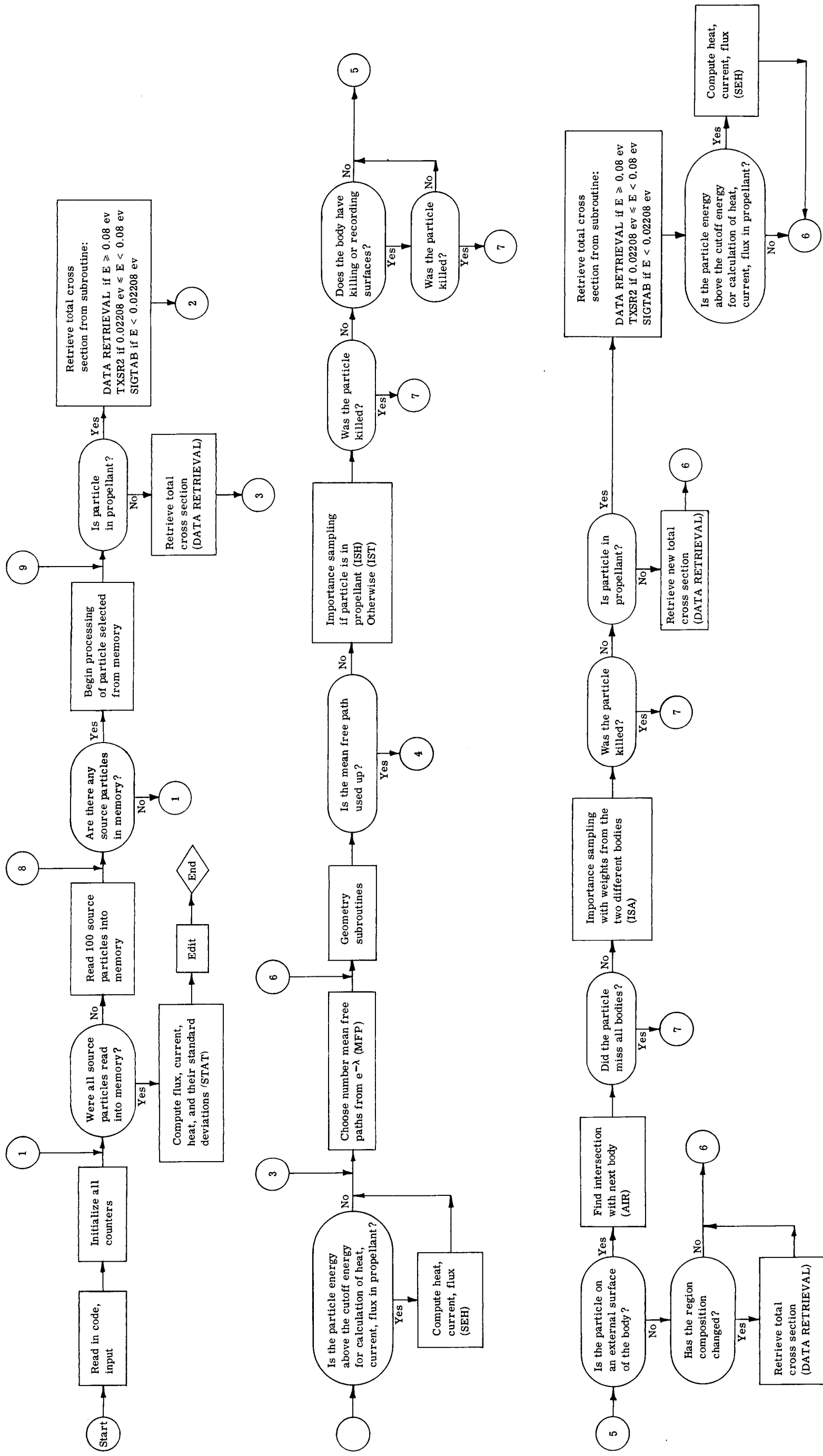
1. 0.20527399×10^6
2. 0.91448089×10^5
3. 0.37050246×10^5
4. 0.23707408×10^5
5. 0.16522805×10^5
6. 0.10364579×10^5
7. 0.31799865×10^4
8. 0.25641643×10^4
9. 0.15377942×10^4
10. 0.71669815×10^3
11. 0.10087615×10^3

8. BIBLIOGRAPHY

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9. FLOW CHART

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